Inelastic Dark Matter in Supersymmetric Inverse Seesaw

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in collaboration with
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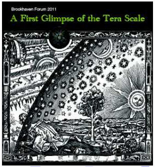
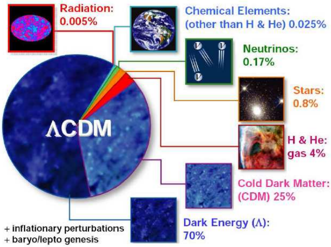
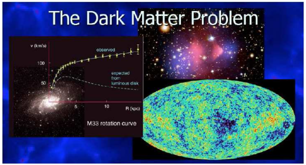


Outline

Dark Matter: Evidence for New Physics beyond SM





- A major evidence for beyond SM physics.
- Dedicated experimental searches to determine the mass and interaction properties of DM.
- Supplement the new physics search at LHC.

Why beyond MSSM?

- Neutral LSP is a natural DM candidate in SUSY models with R-parity.
- Two CDM candidates in MSSM:
  1. Lightest Neutralino $\widetilde{\chi}_1^0$ ($\widetilde{B}^0$, $\widetilde{W}_{3L}^0$, $\widetilde{h}_u^0$, $\widetilde{h}_d^0$): Good DM candidate for $m_{\widetilde{\chi}_1^0} > 18$ GeV (LEP2 + relic density constraints) [Hooper, Plehn '02]
  2. Left Sneutrino $\widetilde{\nu}_L$: Ruled out (invisible Z-width + relic density + direct detection constraints). [Falk, Olive, Srednicki '94; Hebbeker '99]
- For very light DM ($\lesssim 20$ GeV), need to go beyond MSSM.
- Another reason for extensions of MSSM: neutrino mass.
- Can the same extensions of MSSM have a very light DM and observed neutrino parameters?

Seesaw Mechanism and Sneutrino DM

- Add one or more SM singlet heavy neutrino.
- Superpartner of the singlet neutrino(s) with a small admixture of left sneutrino can be the DM.
- Type-I seesaw: Majorana RH neutrino (N). [Minkowski '77; Yanagida '79; Glashow '79; Gell-Mann, Ramond, Slansky '80; Mohapatra, Senjanović '80]

$$\mathcal{L}_{\rm mass} = (\overline{L} M_D N + {\rm h.c.}) + N M_R N$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix}, \quad m_\nu^{\rm light} = -M_D M_R^{-1} M_D^T$$

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- Several models constructed for sneutrino DM with type-I seesaw. [Lee, Matchev, Nasri '07; Allahverdi, Dutta, Mazumdar '07; Arina, Fornengo '07; Thomas, Tucker-Smith, Weiner '08; Deppisch, Pilaftsis '08; Cerdeno, Munoz, Seto '09;...]
- Also non-thermal RH sneutrino DM (either by small Yukawa or low reheating temperature). [Arkani-Hamed, Hall, Murayama, Smith, Weiner '00; Asaka, Ishiwata, Moroi '06; Gopalakrishna, de Gouvea, Porod '06]

Inverse Seesaw

- Add two SM singlet fermions: mostly Dirac N and Majorana S. [Mohapatra '86; Mohapatra, Valle '86]

$$\begin{aligned}
\mathcal{L}_{\rm mass} &= (\overline{L}M_D N + \overline{N} M_R S + {\rm h.c.}) + S\mu_S S \\
\mathcal{M}_\nu &= \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M_R \\ 0 & M_R^T & \mu_S/2 \end{pmatrix}; \\
m_\nu^{\rm light} &\simeq \left(M_D M_R^{-1}\right)\mu\left(M_D M_R^{-1}\right)^T \quad {\rm for}\ \mu \ll M_R
\end{aligned}$$

- TeV scale M_R even with large $M_D \sim m_t$ for $\mu \sim$ keV.
- In contrast with type-I where $M_D \lesssim m_e$ for TeV M_R.
- Smallness of μ is *natural* in 't Hooft sense.

Sneutrino DM in Inverse Seesaw

- Neglecting the $\not{L}$ effect, the complex scalar eigenstate for sneutrino LSP:

$$\widetilde{\chi}_1 = \sum_{i=1}^{3} \left[(U^\dagger)_{1\nu_i} \widetilde{\nu}_i + (U^\dagger)_{1N_i} \widetilde{N}_i^\dagger + (U^\dagger)_{1S_i} \widetilde{S}_i \right]$$

$c_{(0,1,2)} \equiv \sum_{i=1}^{3} |U_{1(\nu_i,N_i,S_i)}|^2$ determines the fraction of each component.

- The $\not{L}$ effect induces the splitting terms $\sum_{m,n=1}^{9} A_{mn} \widetilde{\chi}_m \widetilde{\chi}_n$.
- Leads to two real scalar fields ($\chi_{1,2}$) for the LSP with mass splitting

$$\delta M_\chi = \frac{4|A_{11}|}{M_\chi} \quad (|A_{11}| \sim \mu_S M_{\rm SUSY})$$

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$$\delta M_\chi = \frac{4|A_{11}|}{M_\chi} \quad (|A_{11}| \sim \mu_S M_{\rm SUSY})$$

- Naturally leads to inelastic DM for direct detection since the gauge boson mediator *necessarily* connects χ_1 to χ_2 through the gauge Noether current

$$iZ^\mu (\chi_1 \partial_\mu \chi_2 - \chi_2 \partial_\mu \chi_1)$$

- For $M_{\rm SUSY} \sim$ TeV, typical splitting $\sim$ a few keV (observable range for direct detection).
- Inelasticity of the DM intimately linked to the small Majorana mass of the neutrino.

Inverse Seesaw in Models beyond MSSM

- Inverse seesaw within MSSM gauge group $SU(2)_L \times U(1)_Y$:

$$\mathcal{W}_1 = \mathcal{W}_{\text{MSSM}} + Y_\nu L H_u N + M_R N S + \frac{1}{2} S \mu_S S$$

[Arina, Bazzocchi, Fornengo, Romao, Valle '08]

- Needs to omit terms like LH_uS and NN allowed by the symmetry.
- Could extend the gauge symmetry to $SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ [Khalil, Okada, Toma '11] or global $B - L$ [Josse-Michaux, Molinaro '11].

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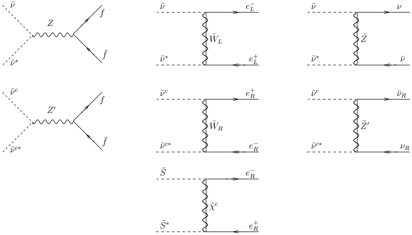
- However, these scenarios do not arise from GUT.
- To realize inverse seesaw at TeV scale within a GUT framework, we use the SUSYLR gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. [BD, Mohapatra '09]
- Minimal inverse seesaw structure arises *naturally* as the $SU(2)_R$ gauge symmetry forbids other terms in the superpotential:

$$\mathcal{W}_2 = \mathcal{W}_{\rm MSSM} + Y_\nu L \Phi L^c + M_R S \phi_R L^c + \frac{1}{2} S \mu_S S$$

Relic Abundance of Sneutrino DM in SUSYLR

$$\widetilde{\chi}_1 \equiv (\widetilde{\nu}, \widetilde{\nu}^{c\dagger}, \widetilde{S})$$



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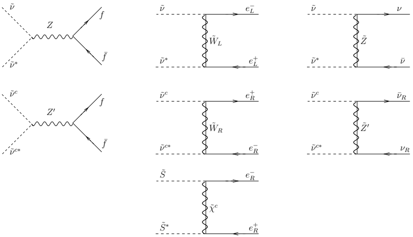
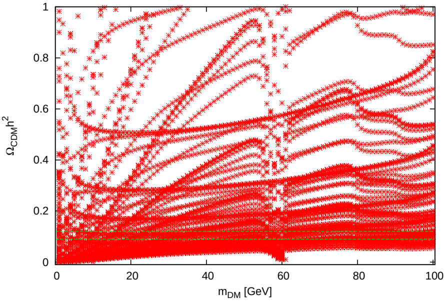
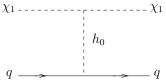




- Relic density and invisible Z-decay width constraint restricts $c_0 < 0.16$.
- Experimental lower bound on Z'-mass restricts $c_1 < 0.5$.
- The annihilation cross section for Z'-channel suppressed compared to Z-channel by factor $(c_1/c_0)^2(M_Z/M_{Z'})^4$.
- Z'-channel important only when c_0 is very small.

Direct Detection



(a)

- Elastic channel due to interaction with light Higgs:

$$\lambda h_0 \widetilde{\chi}_1^\dagger \widetilde{\chi}_1 = \frac{1}{2}\lambda h_0(\chi_1^2 + \chi_2^2)$$

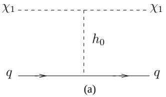
- Elastic scattering cross section

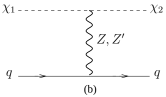
$$\sigma_N^{\rm el} = \frac{\lambda^2 M_N^4 (\sum_q \langle N|m_q\bar{q}q|N\rangle)^2}{4\pi v_{\rm wk}^2 M_h^4 (M_N + M_\chi)^2}$$

with $\lambda = (g_{2L}^2 c_0 + g_{2R}^2 c_1)v_{\rm wk}/4$.

- Suppressed by mass of the light quark (mostly strange).

Direct Detection





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with $\lambda = (g_{2L}^2 c_0 + g_{2R}^2 c_1) v_{\rm wk}/4$.

- Suppressed by mass of the light quark (mostly strange).

- Inelastic channel due to interaction with gauge bosons:

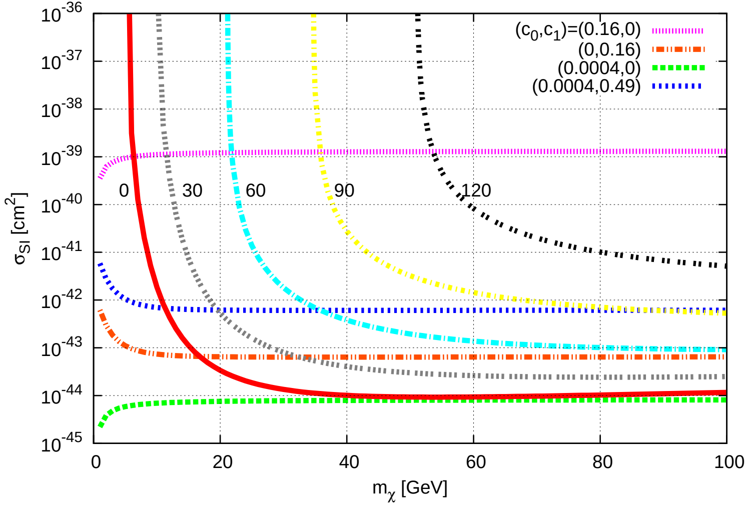
$$i(a_1 Z^\mu + a_2 Z'^\mu)(\widetilde{\chi}_1 \partial_\mu \widetilde{\chi}_1^\dagger - \widetilde{\chi}_1^\dagger \partial_\mu \widetilde{\chi}_1) \\ = i(a_1 Z^\mu + a_2 Z'^\mu)(\chi_1 \partial_\mu \chi_2 - \chi_2 \partial_\mu \chi_1)$$

- Inelastic scattering cross section

$$\sigma_{p,n}^{\rm iel} = \frac{g_{2L}^4 \kappa_{p,n}}{4\pi \cos^4\theta_W M_Z^4} \frac{M_{p,n}^2 M_\chi^2}{(M_{p,n} + M_\chi)^2} \times \left[c_0^2 + c_1^2 \left(\frac{g_{2R}}{g_{2L}}\right)^4 \left(\frac{M_Z}{M_{Z'}}\right)^4 \frac{\cos^{12}\theta_W}{\cos^2 2\theta_W}\right]$$

$$\text{with } \kappa_{p,n} = \left(\frac{3}{4} - q_{p,n}\sin^2\theta_W\right)^2$$

Direct Detection Cross Section

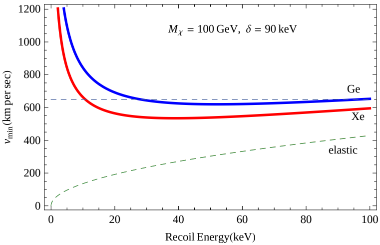


iDM Scattering Rate

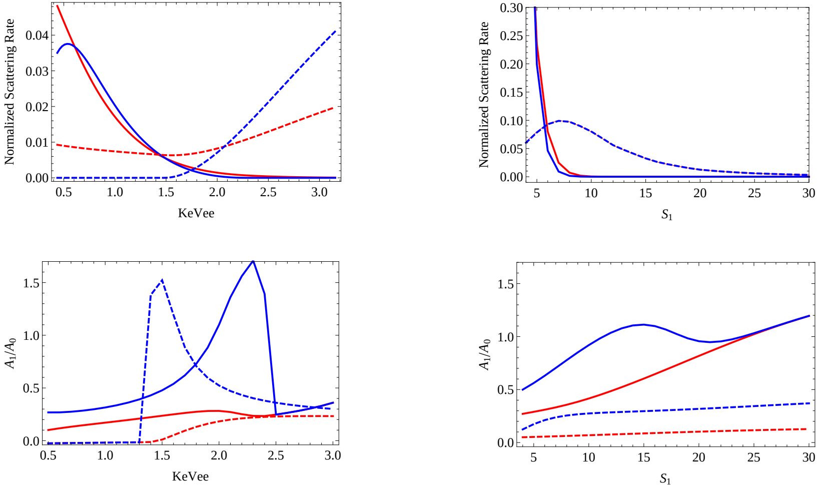
$$\frac{dR}{dE_r} = \frac{\rho_{\chi_1}}{M_\chi} \int_{|\mathbf{v}|>v_{\min}} d^3\mathbf{v} \frac{f(\mathbf{v})}{|\mathbf{v}|} \frac{A_{\text{eff}}^2 \bar{\sigma}_N}{2\mu_{\chi N}} F^2(|\mathbf{q}|)$$

$$v_{\min} = \frac{1}{\sqrt{2M_A E_r}} \left(\frac{M_A E_r}{\mu_{\chi A}} + \delta \right)$$

- Sampling only high-velocity tail of Maxwellian velocity distribution.
- Enhanced annual modulation.
- Threshold velocity for iDM scattering to occur: $v_{\text{threshold}} = \sqrt{2\delta/\mu_{\chi A}}$.
- No events at low recoil energies.
- A peak in the scattering rate.
- Favors target nuclei with heavier mass.



Scattering Rate and Annual Modulation



$$\left[(c_0, c_1) = \begin{cases} (0.001, 0.1) \\ (0.1, 0.001) \end{cases} , \qquad (M_\chi, \delta) = \begin{cases} (10\text{ GeV},\ 20\text{ keV}) & \text{(solid)} \\ (50\text{ GeV},\ 60\text{ keV}) & \text{(dashed)} \end{cases}\right]$$

Collider Signatures

- Characteristic LHC signal depending on the sparticle spectrum. [Belanger, Kraml, Lessa '11].
  - For $m_{\tilde{g}} < m_{\tilde{q}}$, dominant signal is charged di-lepton + four jets + missing E_T.
  - For $m_{\tilde{g}} \simeq m_{\tilde{q}}$, two or three leptons + two jets + missing E_T.
  - For $m_{\tilde{g}} > m_{\tilde{q}}$, one or two leptons + two hard jets + missing E_T.
- In SUSY inverse seesaw, for most of the parameter space, gluino is heavier than the lightest squark (usually stop); might be easier to identify the signal. [An, BD, Cai, Mohapatra (work in progress)]
- Also possible to identify sneutrino LSP from dilepton resonance (true for generic models with $B - L$). [Lee, Li '11]

Conclusion

- SUSY inverse seesaw naturally leads to iDM.
- Light dark matter is favored by the model.
- Could be constrained to be very light (below 20 GeV) by the current and future direct detection bounds.
- Large differential scattering rate and annual modulation predictions can be tested in future direct detection experiments.
- The collider signature is dijet plus same sign charged di lepton with missing $\not{E}_T$.
- May be able to indentify SUSY inverse seesaw by combining collider and direct detection searches.

Backup Slide 1: Fitting CRESST-II